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In-vivo three-dimensional knee kinematics during daily activities in dogs

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ABSTRACT:

The canine knee is morphologically similar to the human knee and thus dogs have been used in experimental models to study human knee pathology. To date, there is limited data of normal canine 3D knee kinematics during daily activities. The objective of this study was to characterize 3D *in-vivo* femorotibial kinematics in normal dogs during commonly performed daily activities. Using single-plane fluoroscopy, 6 normal dogs were imaged performing walk, trot, sit and stair ascent activities. CT-generated bone models were used for kinematic measurement using a 3D-to-2D model registration technique. Increasing knee flexion angle was typically associated with increasing tibial internal rotation, abduction and anterior translation during all 4 activities. The precise relationship between flexion angle and these movements varied both within and between activities. Significant differences in axial rotation and coronal angulation were found at the same flexion angle during different phases of the walk and trot. This was also found with anterior tibial translation during the trot only. Normal canine knees accommodate motion in all planes; precise kinematics within this envelope of motion are activity dependent. This data establishes the characteristics of normal 3D femorotibial joint kinematics in dogs that can be used as a comparison for future studies.

KEY WORDS: canine knee kinematics; single-plane fluoroscopy; 3D-to-2D model registration; daily activities; activity dependence

INTRODUCTION

Understanding knee kinematics in dogs is of considerable interest for both human and veterinary orthopaedists. Given the morphological similarities, the dog is a well-established animal model for investigating diseases and evaluating new treatments for the human knee.[1] The anterior cruciate ligament (ACL) deficient canine model, also known as the Pond-Nuki Model, reliably causes abnormal kinematics, and is thus utilized to investigate the pathogenesis of mechanically-induced osteoarthritis.[2-5] The canine knee has been used as a preclinical animal model for ACL reconstruction methods,[6,7] posterolateral injuries,[8] and meniscal surgery.[9] Additionally, one of the leading causes of pelvic limb lameness in dogs is naturally occurring ACL degeneration, which is estimated to cost US pet owner $1.3 billion annually.[10]

Normal kinematic parameters of the knee in humans vary widely over a range of different daily activities;[11,12] unfortunately, equivalent information for the canine knee is sparsely reported. High-precision 3D *in-vivo* knee kinematics in normal dogs has been described in two experimental studies.[13,14] These investigations were limited by the fact that the primary focus was to assess abnormal motion associated with ACL deficiency, and normal kinematic patterns were not thoroughly described. One of these studies also adopted invasive methodology to track kinematics, which may have influenced natural gait patterns.[13] Additionally, the analyses only evaluated straight-line ambulation. The objective of this study was to determine 3D in vivo kinematics of the healthy canine stifle joint during walking, trotting, stair ascent and sitting using non-invasive methods.

METHODS

Six client-owned, adult Labrador retrievers with a mean age of 4 years (range 1 – 7 years) and mean weight of 28 kg (26 – 32 kg) were studied. The study was approved by the University's Institutional Animal Care and Use Committee and signed owner consent was obtained. A board certified veterinary surgeon (S.E.K) performed an orthopaedic physical examination of each animal to screen for clinically detectable bone or joint pathology. No discernable abnormalities were detected.

Computed tomographic (CT) scans (Toshiba Aquilon 8, Toshiba American Medical Systems Inc, Tustin, CA) with a 512 x 512 image matrix, a 0.35 x 0.35 pixel dim, and 1-mm slice thickness were obtained over the full length of the femora and tibiae. The CT images of the pelvic limbs were reviewed by a veterinary surgeon (S.E.K) to confirm absence of orthopaedic disease in all dogs. The cortical bone margins were segmented using an open source 3D segmentation software program (ITK-SNAP, http://www.itksnap.org), and these point-clouds were converted into polygonal surface models with a reverse engineering software program (Geomagic Inc, Research Triangle Park, NC).[15] Anatomic coordinate systems were applied to each model as previously described for the dog.[14] The center of the ACL origin and insertion were used as the specific points to define joint translations, as previously described.[14] All dogs were habituated to treadmill ambulation, stair ascent and stand-to-sit activities with biweekly training sessions for 1 month prior to data collection. Continuous mediolateral view fluoroscopic images of the knees were acquired during treadmill walk, treadmill trot, stand-to-sit, and stair ascent activities using a ceiling-mounted fluoroscopic system, (Toshiba American Medical Systems Inc, Tustin, CA) and a flat panel detector (Fig.1). Prior to fluoroscopic image acquisition, optical geometry (principal point and principal distance) of the fluoroscopy system was determined using fluoroscopic images of a calibration target.[16] For data collection, images were obtained using a pulse rate of 30 frames/s, pulse width of 1 ms, and an image area of 400 x 300 mm, giving a pixel size of 0.39 mm x 0.39 mm and an image resolution of 1,024 x 1,024 pixels. The x-ray source was configured to supply a 72 kV beam with a 50 mA beam current.

Dogs walked on a treadmill at a velocity of 1.1 m/s (2.5 mph) and trotted at a velocity of 2 m/s (4.5 mph); similar to that previously reported.[17] For the walk and trot, fluoroscopic imaging was obtained for 10 full gait cycles. A full gait cycle was defined as 'paw-strike' to ipsilateral 'paw-strike'. To determine the phase of the gait cycle on the fluoroscopic images, high-speed video recordings (Canon Vixia HF G10, Melville, NY) were captured at 60 frames/sec, with a shutter speed of 1/2000 s, and were visually synchronized with fluoroscopic images during these activities. Custom made stairs, consisting of 3 steps with a rise-height and run-length of 25 cm and 26 cm respectively were utilized for the stair ascent activity. Due to the limited fluoroscopic field-of-view, acquisition of a complete gait cycle during stair ascent was not possible. Stairs were positioned so that the stance phase of stair ascent kinematics could be captured within the fluoroscopic field of view. The stand-to-sit activity involved instructing the dog to sit on command with the pelvic limbs positioned within the fluoroscopic field of view. Thus, stair ascent measured femorotibial kinematics from flexion to full extension while the stand-to-sit activity measured femorotibial kinematics from extension to full flexion. The fluoroscopic videos of stair ascent and stand-to-sit activities began at slightly different flexion angles, due to variability in positioning of the dog within the field of view; thus, a maximum knee flexion angle and maximum knee extension angle common to all subjects were selected as starting points for stair ascent and stand-to-sit activities, respectively.

The 3D positions of the femur and tibia and fibula were determined using a previously described 3D-to-2D shape matching technique.[12,15,16] The reported accuracy of this technique in dogs was found to be within 1.3 mm for translations and 1.6° for rotations; however, it is not recommended to attempt quantification of out-of-plane translation (medial-lateral) with this method.[15,16] We estimated that our fluoroscopic imaging protocol delivered an equivalent ionizing radiation dose of 0.036 μSv per image, or 0.03 mSv per 15 s. The CT bone models were projected onto the fluoroscopic images and manually aligned to the bone projections using shape-matching software (JointTrack, University of Florida: http://sourceforge.net/projects/jointtrack/) (Fig. 2). Three-dimensional femorotibial kinematics were determined from the 3D position of each bone model using cardan angles as previously described.[18] Each gait cycle was time normalized using spline interpolation at 1% intervals from 0-100%. Time normalization allowed averaging of the data across multiple cycles for individual dogs, despite differences in cadence between trials and between dogs. Of the ten gait cycles captured for the walk and trot, the three cycles that subjectively were best captured in the field of view, were chosen for analysis. Due to difficulty in obtaining adequately positioned knee fluoroscopic images, only two stand-to-sit and one stair ascent activities were analyzed in each dog. The kinematics for these two activities were similarly interpolated; a common starting knee flexion angle was used for these activities for all dogs because the phase of activity at the start of fluoroscopic recordings varied widely. One-way ANOVA and Tukey post-hoc tests ($p < 0.05$) were used to examine for differences between and within activities. Pearson correlations were used to assess for any coupling in motion for selected kinematic parameters for each activity within each subject.

RESULTS

Kinematic data for flexion-extension, anterior-posterior translation, internal-external rotation, and abduction-adduction, plotted as a function of time throughout the gait cycle are presented in Figs. 3 – 6. Average flexion patterns for both the walk and trot treadmill gait were similar. A biphasic flexion-extension pattern was observed; swing phase was characterized by large flexion followed by large extension, with the extension continuing into early stance phase, for the remainder of stance phase there was slight flexion followed by slight extension. Trotting encompassed an 18º greater range of flexion-extension motion when compared to walking ($P < 0.05$). The knee flexed to a mean of 150° during sitting, and extended to a mean of 35° during stair ascent for the portion of these activities captured by fluoroscopy (Table 1). Maximum knee extension did not differ between the walk and trot ($P = 0.98$); maximum extension during stair ascent was on average 6º less during walking than during trotting ($P < 0.05$) (Table 1).

Generally, increasing flexion was associated with increased internal tibial rotation for most activities; the exact relationship between axial rotational alignment and flexion angle varied both within and between activities (Fig. 7~~3~~). During walking and trotting, external rotation of the internally rotated tibia occurred during terminal extension of swing phase and continued into stance phase. During the swing phase, the tibia rotated from 1° of external rotation to 8° of internal rotation, and from 4° of external rotation to 11° of internal rotation for the walk and trot, respectively. The tibia then began externally rotating at the end of swing phase. Overall, axial rotational range of motion was greater during trotting than while walking ($P < 0.01$) (Table 1). Offset, which was defined as significant differences in secondary displacements of the knee observed at identical flexion angles within and between activities,[19] was evident for axial rotational alignment during walking and trotting. Axial alignment offset was detected at the four measured flexion angles (50º, 60º, 70º and 80º). For instance, at a knee flexion angle of 60° for the trot, there was external tibial rotation of 2° during early swing phase, and internal tibial rotation of 11° during early stance phase ($P=0.03$). When the entire gait cycle was analyzed collectively, there was a positive correlation between internal rotation and flexion in all dogs during walking ($r = 0.61 – 0.89$), and in 4 of 6 dogs during trotting ($r = 0.62 – 0.79$). Coupling between internal-external rotation and flexion-extension during stair ascent was evident in only 3 of 6 dogs ($r = 0.68 – 0.94$). During deep flexion of sitting, internal rotation was coupled with flexion in all dogs ($r = 0.57 – 0.88$), but axial rotational alignment was still within the range observed during other activities despite the deeper flexion found during the sit activity (Fig. 7~~3~~).

Increased flexion inconsistently correlated with increased abduction angulation across the range of activities (Fig. 8~~4~~). Abduction was correlated with flexion angle in 4 of 6 dogs for both the walk ($r = 0.85 – 0.96$) and the trot ($r = 0.26 – 0.96$). During trotting, a mildly abducted tibia gradually adducted over the duration of stance phase; during walking the joint was in neutral coronal plane alignment at pawstrike, but became mildly adducted over stance phase. During swing phase, the tibia angulated from 4° of adduction to 1° and 4° of abduction for the walk and trot, respectively. Adduction coincided with extension during swing phase. Overall, coronal angulation range of motion was not different between activities (Table 1). Offset was also evident for coronal angulation during walking and trotting, at the four flexion angles (50º, 60º, 70º and 80º) measured. For instance, at a knee flexion angle of 60° for the trot, there was abduction of 2° during early swing phase, and adduction of 2° during late swing phase (P= 0.04). Coronal angulation alignment during knee extension for stair ascent resembled the pattern observed during walking, though significant correlation between abduction and axial rotation was observed in only 3 of 6 dogs (r = 0.56 – 0.90). During deep flexion of sitting, mild abduction was coupled with flexion in 5 of 6 dogs (r = 0.30 – 0.86), but coronal angulation alignment was within the range observed during other activities that had greater knee extension.

Anterior tibial translation was nominal, but was correlated with increasing knee flexion angle in all dogs during sit (r = 0.55 – 0.93), in 3 of 6 dogs during stair climb (r = 0.60 - 0.93), and in 5 of 6 dogs for the walk (r = 0.57 – 0.85) and trot (r = 0.43 = 0.70) (Fig. 9~~5~~). At maximal extension of the trot and walk, the tibial origin was 13 mm anterior to the femoral origin. The tibial origin translated anteriorly by 2 mm and 3 mm during peak flexion of the swing phase for walking and trotting, respectively (Table 1). Deeper flexion caused by sitting induced the greatest anterior tibial translation, where the tibial origin was 18 mm anterior to the femoral origin in full flexion (Table 1). Offset was also evident for anterior-posterior translations during the trot, but not the walk. Offset for the trot was detected at two flexion angles (40º and 50º). For instance during the trot at a knee flexion angle of 50º, the tibial origin was 13 mm anterior to the femoral origin during swing phase, and 14.9 mm anterior to the femoral origin during the stance phase (P =0.04).

DISCUSSION

Using single-plane fluoroscopy, we demonstrated that normal *in-vivo* femorotibial joint kinematics in dogs are complex, where 3D joint alignment is dependent on the type of activity performed. Our study highlighted that a wide range of joint poses were evident during the daily activities that were assessed. Similar to what has been observed in the human knee,[12,19,20] there appears to be tight active control of 3D knee alignment in dogs.

Significant correlations were observed between internal tibial rotation and knee flexion in the majority of dogs during most activities. Much of this coupled motion between axial rotation and flexion is consistent with findings from cadaver studies investigating the contribution of passive restraints to canine knee motion. Anatomic studies have shown that relaxation of the lateral collateral ligament occurs during flexion, which allows the tibia to internally rotate.[21,22] Known as the 'screw-home' mechanism, the coupling between axial rotation and flexion-extension is also recognized in the human knee under passive conditions.[23,24] *In-vivo,* internal tibial rotation during deep knee flexion in humans has been reported;[11,12] however, this pattern is not typically recognized during activities requiring greater knee extension such as walking.[19,20] We found internal rotation to be significantly correlated with knee flexion in the majority of dogs, and while a direct comparison cannot be made between species with our study design, it would appear that the 'screw-home' mechanism is more prominent in dogs when compared to what has been observed in humans.

Axial rotational alignment differed at equivalent flexion angles during treadmill ambulation, revealing offset during *in-vivo* dynamic activities for the canine knee. We suspect this difference is the result of multiple factors, including gravitational, inertial, and muscle forces.[19] For instance, internal rotators of the tibia such as the popliteus, gracilis, semimembranosus, and sartorius mm. are also flexors of the knee, and are likely to be predominately contracting when there is active knee flexion. Dyrby et al., highlighted very similar characteristics of knee motion during walking in humans, where greatest external tibial rotation during ambulation was present during late swing phase, and the tibia internally rotated throughout stance phase.[19] Accordingly, the pathway of knee motion in dogs within the 'envelope of dynamic laxity' cannot be exclusively derived from the passive characteristics observed from anatomic studies.

Coronal plane angulation was more tightly constrained than axial rotation, where the knee did not angulate by more than 8° in abduction and adduction. This finding is consistent with cadaver investigations demonstrating the important contributions of the collateral ligaments to knee stability in dogs.[22] While coupling between increased flexion and knee abduction was not as obvious as the relationship between flexion and internal rotation, a significant correlation was found in at least half of dogs during all activities. Increased abduction with flexion may be predominately caused by the normal posterior sagittal slope of the tibial plateau in dogs, which is much steeper than the slope of the human knee: when the tibia internally rotated upon flexion, it is possible that the lateral femoral condyle is positioned on the more distal, posterior aspect of the lateral tibial condyle, whereas the medial femoral condyle is articulating on the more proximal, anterior aspect of the medial tibial condyle. Defining joint contact pathways in each compartment may shed further light on the pattern of coronal angulation observed in our study.

Changes in anterior tibial translation were likely caused by two distinct processes. First, there was a significant correlation in most dogs between increasing flexion angle and anterior tibial translation across all activities. This feature reflected the cam-shaped morphology of the femoral condyles, which roll posteriorly on the tibial plateau during flexion.[25] Second, a mild but significant offset in anterior-posterior alignment was found during trotting. A change of up to 1.9 mm was identified at equivalent flexion angles but differing phases within the gait cycle. This offset was caused by greater anterior tibial translation observed during the stance phase of gait, and is consistent with the tendency of the femoral condyles to slide down the posterior tibial slope during weight-bearing,[26] and quadriceps contraction generating an anterior pull on the tibia.[27] In the invasive kinematic study of the canine stifle by Korvick et al., this pattern of anterior tibial translation during weight-bearing in normal dogs was not observed.[13] We suspect our data is a better representation of normal kinematics, as the presence of cortical half pins in the Korvick study created lameness in 2 of 5 dogs, thus potentially mitigating the loads driving anterior translation. We identified offset in anterior translation during trotting but not walking, which is also similar to the human knee where functional tasks of increasing demand induced greater anterior tibial translation.[28]

There are several limitations to our study. Data were obtained using single-plane fluoroscopic imaging, which is less accurate for measuring out-of-sagittal-plane motions than biplanar systems.[15,16] This limitation precluded the ability to accurately assess medio-lateral translations. The image capture frequency of our set up was also slower than what has been reported in prior fluoroscopic studies of dogs.[17] Furthermore, the flat panel detector has a defined field of view, which only allowed us to capture the stance portion of stair ascent. Treadmill kinematics has been shown to be different to that over ground in dogs;[29] thus our kinematic findings may vary slightly from what occurs in normally ambulating dogs over ground. We were also only able to analyze a small number of trials for each subject. Lastly, our results may not be representative of gait patterns in other dog breeds due to variations in size, conformation and cadence.

Femorotibial kinematics in dogs involves complex 3D motion during normal daily activities. Knee movements occur within an envelope of motion, which vary according to the activity performed and likely to be heavily influenced by the combination of internal and external forces and moments acting across the joint. Further studies that elucidate the precise kinetic and geometric characteristics of canine knee during normal daily activities are warranted to improve insight into the complexity of this joint.

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Figure Legends

Figure 1. Dog walking with the C-arm positioned to acquire lateral-view fluoroscopic knee images (A). Stairs positioned to capture stance-phase of stair ascent (B). Dog positioned after completing stand-to-sit exercise (C).

Figure 2. Representative shape-matched fluoroscopic image of a dog knee at the trot. 3D bone models from 5 different phases of the gait cycle are included to demonstrate capture of the complete gait cycle on the flat panel detector.

Figure 3. Knee kinematics during walking, group average curves. Plots show the mean (solid line) ± 1 standard deviation (shaded regions) for anterior-posterior translation (top left), internal-external rotation (bottom left), flexion-extension motion (top right), and abduction-adduction motion (bottom right) from all 6 dogs. 'Gait cycle' is represented from paw strike – paw strike, through both stance and swing phases.

Figure 4. Knee kinematics during trotting, group average curves. Plots show the mean (solid line) ± 1 standard deviation (shaded regions) for anterior-posterior translation (top left), internal-external rotation (bottom left), flexion-extension motion (top right), and abduction-adduction motion (bottom right) from all 6 dogs. 'Gait cycle' is represented from paw strike – paw strike, through both stance and swing phases.

Figure 5. Knee kinematics during stair ascent, group average curves. Plots show the mean (solid line) ± 1 standard deviation (shaded regions) for anterior-posterior translation (top left), internal-

external rotation (bottom left), flexion-extension motion (top right), and abduction-adduction motion (bottom right) from all 6 dogs. ‘Gait cycle’ is represented from the beginning to end of propulsion, or stance phase.

Figure 6. Knee kinematics during sitting, group average curves. Plots show the mean (solid line) ± 1 standard deviation (shaded regions) for anterior-posterior translation (top left), internal-external rotation (bottom left), flexion-extension motion (top right), and abduction-adduction motion (bottom right) from all 6 dogs. ‘Gait cycle’ is represented from standing to sitting.

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Figure 7~~3~~. Averaged plots of knee flexion angle versus axial tibial alignment for all activities. Increased flexion was associated with internal tibial rotation for all activities. Plot arrows indicate direction of movement.

Figure 8~~4~~: Averaged plots of knee flexion angle versus coronal angulation for all four activities. Increased flexion was associated with abduction for all activities.

Figure 9~~5~~: Averaged plots of knee flexion angle versus anterior-posterior translations for all four activities. Increased flexion was associated with anterior tibial translation for all activities.

Tables

TABLE 1. Average maximum, minimum and range of motion kinematics for all dogs during all 4 activities.

Trot				
	Flexion Angle	Internal Rotation	Abduction Angle	Anterior Translation
Maximum	93° (4)	11° (7)	4° (4)	15.5 mm (1.6)
Minimum	36° (7)	-4° (7)	-4° (3)	12.7 mm (1.9)
Range of Motion	57° (6)	15° (3)	8° (5)	2.8 mm (0.9)

Walk				
	Flexion Angle	Internal Rotation	Abduction Angle	Anterior Translation
Maximum	75° (12)	9° (7)	1° (3)	14.7 mm (1.5)
Minimum	35° (6)	-1° (8)	-5° (2)	12.5 mm (2.0)
Range of Motion	40° (9)	10° (5)	6° (3)	2.2 mm (1.2)

Stair Ascent				
	Flexion Angle	Internal Rotation	Abduction Angle	Anterior Translation
Maximum	82°*	2° (7)	0° (5)	14.5 mm (0.7)
Minimum	37° (1)	-6° (7)	-4° (2)	13.1 mm (1.2)
Range of Motion	45°	8° (4)	4° (4)	1.4 mm (0.8)

Sit				
	Flexion Angle	Internal Rotation	Abduction Angle	Anterior Translation
Maximum	150° (3)	3° (5)	4° (7)	17.2 mm (1.5)
Minimum	110°*	-3° (5)	-2° (5)	15.1 mm (1.4)
Range of Motion	40°	6°(3)	6° (4)	2.1 mm (1.0)

Data in parentheses indicate ± 1 standard deviation.

* These values were manually selected as a starting flexion angle common to all dogs, for the stair and sit activity.